DRAFT

Design of a Monitoring Network for Chesapeake Bay and its Tidal Tributaries

22 November 2004

Introduction

An extensive monitoring network exists for the Chesapeake Bay ecosystem. The majority of the monitoring occurs within the framework of the Chesapeake Bay Program (CBP), which was instituted in 1983. The monitoring network that exists today has evolved since 1983 to meet long-standing and emerging needs of Chesapeake Bay resource managers. The initial monitoring network addressed 3 objectives – characterization of existing water quality conditions, detection of changes or trends in water quality indicators and increased understanding of ecosystem processes affecting Bay water quality and the linkage between water quality and living resources. Recent developments affecting the goals and objectives of the CBP monitoring program include the Chesapeake 2000 Agreement, emergence of the total maximum daily load (TMDL) program as a major regulatory issue, and new designated uses and water quality criteria for Chesapeake Bay tidal waters. These developments, as well as competition for limited resources to monitor and assess long-standing and emerging management questions, has prompted an effort to evaluate the existing tidal monitoring program and to identify specific changes needed to address any critical deficiencies. A monitoring network design team (design team) was formed under the auspices of the Tidal Monitoring and Analysis Workgroup (TMAW) of the CBP Monitoring and Analysis Subcommittee (MASC) and charged with designing a monitoring network that addresses anticipated CBP needs and constraints. The design team comprises individuals representing a cross-section of institutional affiliations and areas of expertise (Appendix A). This report documents the process and rationale followed by the design team to arrive at its recommendations.

Overview of Design Process

The team adopted a top-down approach to program design (Figure 1). First, the design team identified broad programmatic goals and objectives. Based on these goals and objectives, the design team derived specific information requirements. The design team then identified alternative sampling designs and data collection methods capable of yielding the requisite information. Finally, the team evaluated the alternatives and designed a monitoring network that will yield the requisite data and support programmatic goals and objectives.

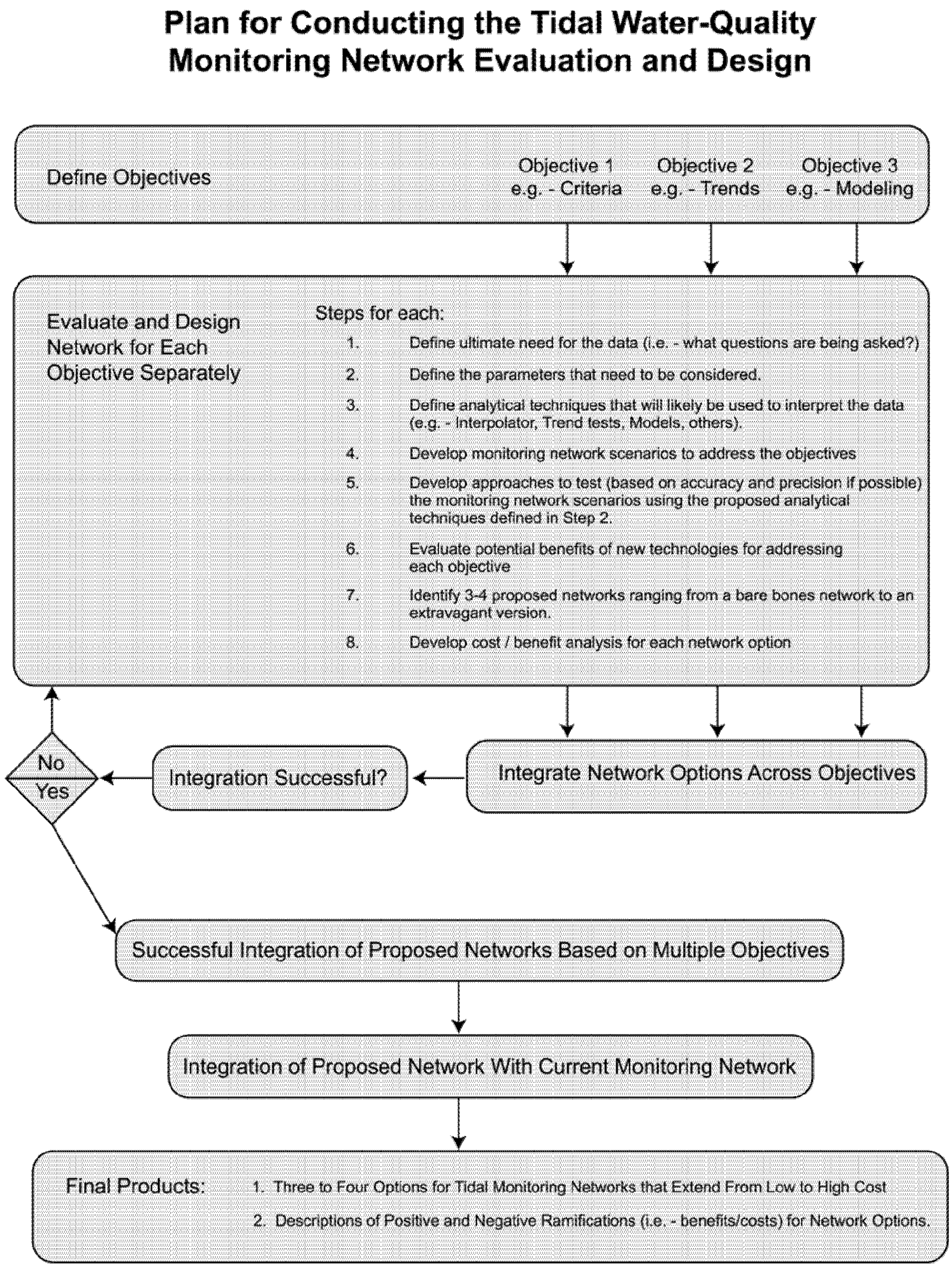

Figure 1. Approach for monitoring network design.

Relevance and feasibility of the resulting design was assured through extensive consultation with the MASC Tidal Monitoring and Assessment Workgroup (TMAW) and other Bay Program elements as the design process unfolded. The design team considered costs, but did not assume or prescribe a specific level of funding. Rather, the design team set forth options representing a range of costs, thereby reserving cost-related decisions for the appropriate decision-makers while documenting the technical advantages and disadvantages of a reasonable set of alternatives.

Monitoring Goals and Objectives

The highest priority of the Chesapeake Bay Program has been the protection and restoration of the living resources of the Bay. Central to attainment of that priority is restoration of the water quality required to sustain those living resources. Consequently, comprehensive monitoring encompasses both the drivers of water quality and indicators of the biological response to changing water quality. The goal of the monitoring program is to collect information for a suite of the most important variables with sufficient temporal-spatial resolution and coverage to meet regulatory requirements, inform management and restoration, and support related education and research. Specific monitoring objectives are described in the following section.

Conceptual Framework for Monitoring Network Design

Monitoring network design encompasses what, when, where, and how data are collected. Design of a comprehensive monitoring network for Chesapeake Bay must address six design factors:

- monitoring objectives,
- designated uses,
- geographic location and salinity regime,
- parameters,
- sampling design, and
- collection methods.

Some combinations of the above factors represent specific information needs, and others represent alternative, parameter-specific strategies and methods of data collection. There are a huge number of possible combinations encompassed by these six factors. The challenge before the design team was to reduce the number of possible combinations among these six factors to a tractable set of alternatives, and to evaluate that set of alternatives to identify a subset that can be expected to efficiently meet all of the monitoring program goals and objectives.

The following subsections describe each of the design factors, how they interact with respect to network design, and the criteria by which the design factors were evaluated to arrive at a recommended monitoring network design.

Monitoring Objectives

Monitoring to support CBP goals must encompass four monitoring objectives:

- Characterization
- Change detection
- Modeling support
- Support of research and education

Characterization constitutes determination of the status of selected water quality and living resource variables within well-defined windows of time and space. A key role of characterization is support of assessments of water quality criteria attainment (i.e., regulatory support). The design team identified assessment of attainment or non-attainment of the new water quality criteria for D.O., water quality criteria and chlorophyll a as the critically important objective of the monitoring program. The new water quality criteria developed for the Bay present a number of new monitoring requirements that are a major driver of the monitoring network design effort. The water quality criteria have not yet been formally incorporated into Maryland and Virginia's water quality standards, but it is anticipated that they will be finalized by early 2005. The provisional water quality criteria that the design team based its recommendations upon are listed in Appendix B. Characterization is also required with respect to nutrient variables and various biotic indicators.

Change detection constitutes detection of trends in water quality and living resource variables over the course of two or more years. Natural year-to-year variation is an inescapable feature of Bay water quality. Detection of improvements or deterioration of water quality, however, is essential for effective management and restoration. This objective addresses the programmatic need to discern human-induced changes in the presence of natural background variation.

Mathematical models are an essential tool for applying existing knowledge and data to predict ecosystem responses to management actions. Mathematical models are also important tools for enhancing understanding of key processes controlling Bay restoration and for structuring and scaling management actions. Monitoring data are critically important to refine the model structure and to calibrate and verify the mathematical models that are so important to the Bay restoration effort. Consequently, the monitoring network must support refinement and rigorous calibration and verification of CBP models.

While existing knowledge of environmental processes affecting Bay restoration is sufficient to inform many key management decisions, research is critically important for maximizing the effectiveness of restoration efforts, for coping with emerging problems, and for identifying critical thresholds. Long-term monitoring defines the environmental context, knowledge of which is needed for effective research to support Bay restoration. The monitoring encompassed by this design process will be a major source, if not the source, of data for long-term records.

Chesapeake Bay is a focal point for environmental education in the Bay region. Indicators of environmental condition in the Bay are of immense interest and value to students and educators. Data that are sufficient to support the goals of characterization and change are also sufficient to support the third objective, education. Information ranging from raw data to derived indicators is of use depending on the grade level and depth of interest.

While support of research and education is considered an objective of CBP monitoring, it cannot be used as a basis of network design because the specific data needs for these objectives are not predetermined. As a result the fourth objective was retained on the list as one of the primary purposes for CBP monitoring, but it was not used as a basis for network design. Instead, the network was designed primarily to address the first three objectives of characterization, change detection and modeling. To a large extent, monitoring that is sufficient to attain the first three objectives is adequate to meet the needs of much of the fourth.

Designated Uses

Waters of the Bay and tidal tributaries are classified by designated use under the EPA document entitled Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay and its Tidal Tributaries (USEPA 2003). Five designated uses have been defined under the new water quality standards for Chesapeake Bay:

- Migratory fish spawning and nursery use
- Shallow-water bay grass use
- Open-water fish and shellfish use
- Deep-water seasonal fish and shellfish use
- Deep-channel seasonal refuge use

With the exception of migratory fish spawning and nursery use, these designated uses do not overlap in space (Figure 2). Migratory fish spawning and nursery use, where the designation exists, overlaps with shallow-water bay grass use and with open-water fish and shellfish use. Further description and rationale for these designations can be found at http://www.chesapeakebay.net/uaasupport.htm.

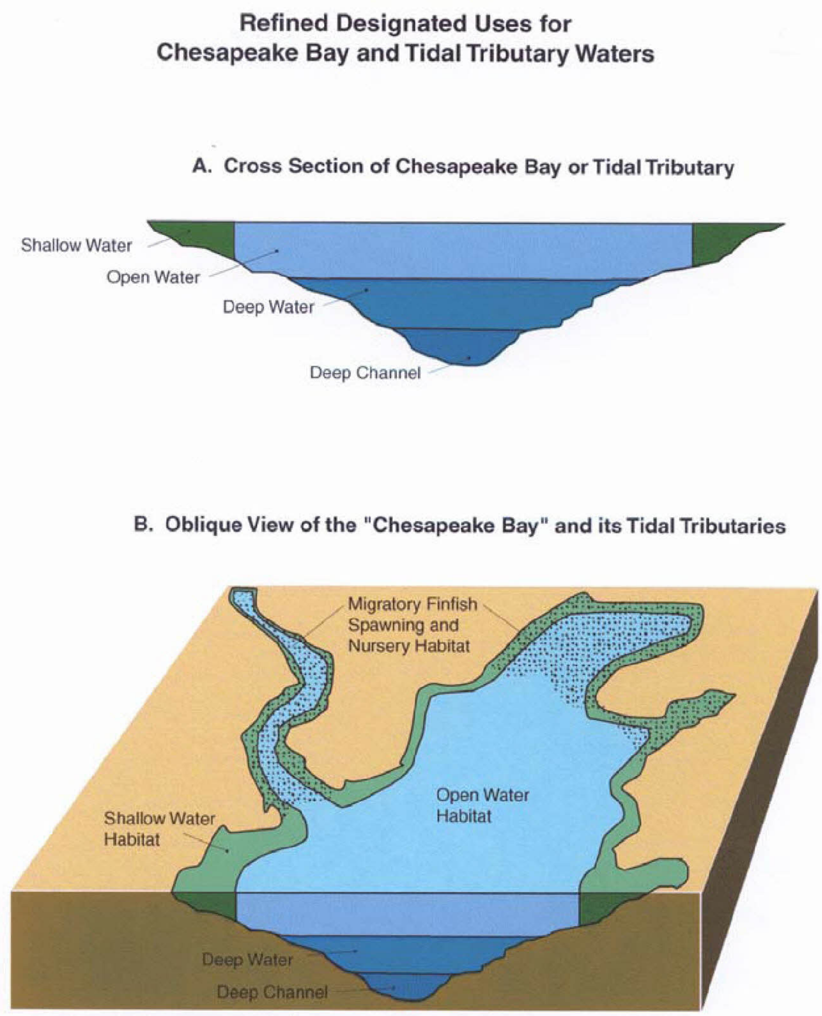

Figure 2. Schematic depiction of designated uses for Chesapeake Bay and tidal tributary waters. Source: __________.

Criteria have been established for specific water quality parameters to ensure attainment of these designated uses. Characterization and change detection with respect to these designated uses and the water quality criteria that derive from them are the primary end use of the monitoring data. Water quality and biotic parameters associated with each of these designated uses are depicted in Table 1.

Table 1. Applicability of the three water quality parameters to the five designated uses for Chesapeake Bay tidal waters.

Designated Use	Parameter: Dissolved Oxygen	Parameter: Chlorophyll a	Parameter: Water Clarity
Migratory spawning and nursery	●	●	
Shallow water	●	●	●
Open water	●	●	
Deep water	●		
Deep channel	●		

Geographic Location and Salinity Regime

The monitoring design encompasses Chesapeake Bay and the tidal portions of Bay tributaries. This large geographic area is subdivided into 77 segments using a segmentation scheme, based in part on salinity regime, that has been in place since 1993 with only minor changes (Figure 3).

The intersection of Bay segments and designated uses defines the spatial units for water-quality assessment, hereafter termed assessment units. Table 2 lists the number of assessment units by designated use and major segment grouping. Note that not all designated uses are present in all Bay segments. For example, deep-channel seasonal refuge use exists only in the central and lower segments of the mainstem of the Bay. Likewise, deep-water seasonal fish and shellfish use does not exist in Bay segments encompassing the uppermost, tidal fresh portions of Bay tributaries.

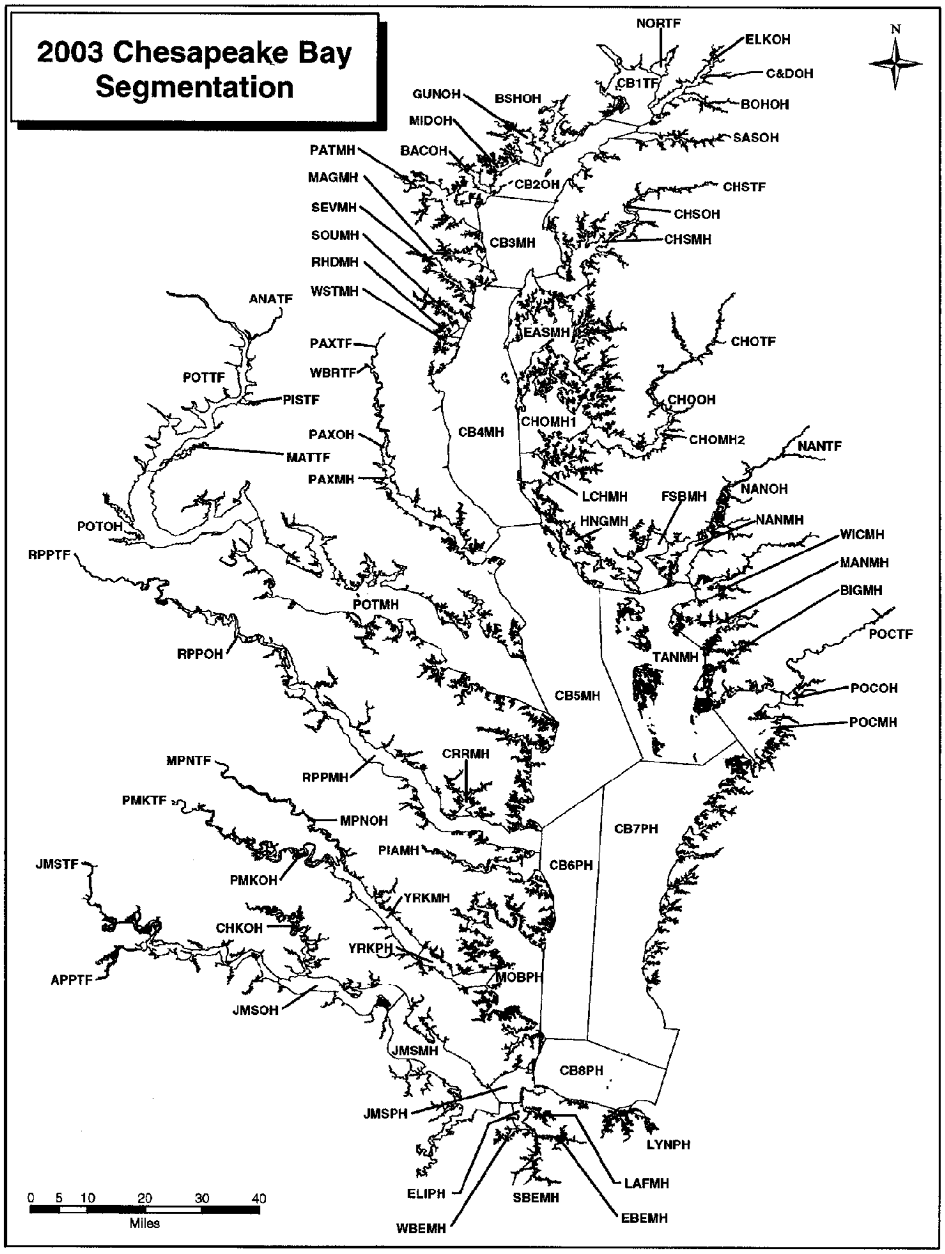

Figure 3. Segmentation scheme used by the Chesapeake Bay Program and adopted for monitoring network design. Source: __________.

Table 2. Number of assessment units encompassed by the Chesapeake Bay non-tidal monitoring network design, by segment type and designated use.

	Number of Assessment Units			
	Segment Type			
Designated Use	**Mainstem**	**Major Tributary**	**Minor Tributary**	**Total**
Migratory fish spawning and nursery use				62
Shallow-water bay grass use				71
Open-water fish and shellfish use				78
Deep-water seasonal fish and shellfish use				15
Deep-channel seasonal refuge use		0	0	10
Total				236

Ultimately, water-quality and resource conditions will be reported for each assessment unit. Monitoring design may differ among major segment groups and designated uses because of differing number and spatial extent of the assessment units and because of differences among assessment units in their spatio-temporal variance characteristics. For example, assessment units comprising shallow water use in minor tributaries are much more numerous than are deep-water fish and shell fish use in mainstem segments. While the shallow water assessment units are relatively small, water quality parameters within them may vary on relatively small spatial scales and over relatively short time scales. Conversely, a parameter such as dissolved oxygen concentration changes relatively slowly in the deep channel, and it exhibits less variation at small spatial scales. Consequently, the required sampling intensity may be less in those assessment units.

Parameters

Within each monitoring objective there are multiple sub-objectives. For example the objective of characterization encompasses determination of current conditions (i.e., status) with respect to water quality criteria, water quality goals, and biotic indicators. The objective of change detection encompasses the same suite of parameters as characterization. Water quality criteria exist for dissolved oxygen, water clarity, and chlorophyll *a*. Additionally, water quality goals have been established for total nitrogen, total phosphorus, and sediment. Biotic indicators include density and composition of phytoplankton, zooplankton, and benthos; submerged aquatic vegetation (SAV) coverage; and chlorophyll a concentration. Not all analytes and indicators are relevant for all designated uses. Table 3 lists parameters that were explicitly considered during network design. The existing monitoring network includes additional parameters, and future monitoring may encompass a similar set of parameters. Inclusion of additional parameters is not expected to affect network design.

Table 3. Parameters considered during network design.

Dissolved oxygen	Phytoplankton	Temperature
Chlorophyll a	Zooplankton	Salinity
Total nitrogen	Benthos	Turbidity (water clarity)
Total phosphorus	SAV	
Sediment		

Sampling Design

Whereas monitoring network design encompasses what, when, where, and how measurements are made, sampling design refers to the procedure by which measurements are distributed in space and time. This occurs at two major levels of space and time. Generally, all assessment units are sampled every year to support annual assessments. This is required to meet the characterization and change detection monitoring objectives. As noted above, however, the shallow water assessment units are probably too numerous to be assessed every year given expected financial constraints. It is likely that a subset of shallow water assessment units will be sampled each year on a prioritized schedule established by the State of Maryland and the Commonwealth of Virginia.

For logistical reasons, the monitoring designs considered here all sample systematically through time within years. This allows for scheduling of vessels, field crews, and maintenance of equipment.

Three major sampling design alternatives were considered for spatial allocation of measurements within assessment units. One alternative is probability-based sampling, in which each sampling unit has a known, non-zero probability of being sampled. An alternative is fixed station sampling, in which measurements are made repeatedly over time at the same location(s). The third alternative is systematic sampling, in which measurements are made at fixed intervals in space. The choice to be made among these major alternatives depends on a number of factors, including the parameter (i.e., analyte or variable) and the technical tools available for measurements. For example, chlorophyll data can be collected quasi-continuously along a systematically structured array of transects, while zooplankton must be collected and analyzed as a relatively small number of discrete samples.

Probability-based Sampling

Probability-based sampling has the principal advantage of ensuring that the sample is representative of the population of interest (set of all sample units within the assessment unit). Probability-based sampling is of particular interest when it is necessary to characterize an assessment unit based on a set of measurements that is small in relation to the set of all sample units, and the representativeness of a small, arbitrarily chosen sample is unknown. While rigorous statements can be made regarding the specific sites observed under a probability-based sampling design and inferences can be made regarding the entire assessment unit and for strata within the assessment unit for which enough observations exist, with probability-based sampling there is no guarantee that measurements will be made in specific sample units at all or on a frequent enough return interval. Furthermore, probability-based samples can complicate logistics and result in distribution of observations that is suboptimal for spatial interpolation.

Systematic Sampling

Systematic sampling is most appropriate when the sample size is large and adjacent measurements are correlated. Systematic sampling ensures measurements are distributed evenly across the area of interest and is best used to support interpolation of conditions between sample points. Systematic sampling can give misleading results if sampling frequency is too low in relation to the scale at which significant variation occurs.

Fixed-station Sampling

Fixed station sampling is useful when conditions at a relatively small number of specific locations are of interest, and when conditions elsewhere within the assessment unit can be reliably inferred from conditions at the fixed stations, for example by spatial interpolation. Fixed station sampling can improve power to detect trends at the locations where measurements are made, but the reliability of broad scale inferences depends upon the validity of the analytical tools and assumptions used to expand the sample to characterize the entire assessment unit.

Collection Methods

Various methods are available for capturing the data in the field. Methods considered include remote sensing (aerial overflight, satellite), grab samples (cruises), buoy systems and other in situ, fixed sensors, and continuous underway monitoring (i.e., Acrobat, Dataflow). As for other aspects of the overall monitoring design, the choice of collection method must consider multiple factors, and may differ depending on the particular type of measurement involved as well as the appropriate sampling design given the spatio-temporal variation characteristics of the measured variable. Table 4 summarizes the advantages and disadvantages of collection methods considered for inclusion in the monitoring network.

Table 4. Advantages and disadvantages of collection methods considered for inclusion in the monitoring network.

1. Remote Sensing (Aerial Overflights, Satellite Imagery (?))
   - Potential Parameters Monitored: Chlorophyll, Turbidity
   - Advantages:
     a. Covers large spatial area quickly and comprehensively (treated as instantaneous)
     b. Provides spatial maps of parameters measured.
   - Disadvantages:
     a. Limited in the number of parameters it can measure.
     b. Expensive.
     c. Limited in temporal frequency.
     d. Does not cover entire tidal area.

2. Grab Samples (Fixed-Station Monitoring)
   - Potential Parameters Monitored: All parameters for all objectives
   - Advantages:
     a. Comprehensive long-term temporal records are generated.
     b. Allows model calibration and detailed trend analysis.
     c. Interpolator can be used to spatially extrapolate information.
     d. Multiple depths can be monitored.
   - Disadvantages:
     a. Generates data sets with limited spatial coverage.
     b. Data is by nature spatially biased since sites tend to be targeted.
     c. Relatively expensive to conduct.
     d. Limited number of sites that can be operated.

3. Fixed Location In Situ Sensors
   - Potential Parameters Monitored: dissolved oxygen, temperature, salinity, turbidity , chlorophyll
   - Advantages:
     a. Continuous data record round the clock.
     b. Low maintenance on a daily basis.
     c. Reliable technology
     d. Real-time data capabilities providing for event based response
     e. Can cover many sites with few staff
     f. Nutrients collected during calibration
   - Disadvantages:
     a. Expense – cost for each buoy.
     b. Limited number of sites that can be monitored.

Table 4 (cont.) Advantages and disadvantages of collection methods considered for inclusion in the monitoring network.

4. Continuous Underway Monitoring Systems (Data Flow, Scan Fish, In Vivo Fluorescence)

- Potential Parameters Monitored: Dissolved Oxygen, Temperature, Chlorophyll, Turbidity, Salinity
- Advantages:
    a. Generates continuous spatially detailed records along a transect.
    b. Interpolator can be used to spatially extrapolate information.
    c. Can cover a large area relatively quickly.
    d. Nutrients collected during calibration
- Disadvantages:
    a. Only one depth can be monitored (Data Flow, In Vivo Fluorescence).
    b. Less accurate than actual measurement (Turbidity, Chlorophyll)
    c. Relatively high initial costs

Remote Sensing

The principle advantage of remote sensing is that it provides broad-scale spatial coverage with fine-scale resolution. Satellites provide virtually instantaneous measurements over the entire Chesapeake Bay with spatial resolution of 1 km^2. Sensors placed in low-flying aircraft yield finer-scale spatial resolution at the expense of spatial coverage. Cloud cover can interfere with data collection, and calibration of remote measurements with *in situ* conditions can be problematic under some circumstances. Security-related flight-path restrictions also are a potential problem with aircraft-based data collection.

Costs of obtaining remotely sensed data can be relatively low, because costs of the infrastructure supporting the data collection are spread over many users; however, fulfillment of data requirements for this monitoring network using aircraft-borne instruments would require that the monitoring program commission additional flights and bear most if not all of the incremental cost.

Grab Samples

Grab samples require that a field crew be on-site at the time the measurement (or collection) is made. Usually this involves a boat, although grab samples can also be collected from piers or bridges. The major cost involved with this collection method is getting people and equipment to each location; the suite of measurements made, however, can be expanded at little additional cost. Grab samples are typically used for biological measurements and for collections that require laboratory analysis; however, in situ measurements can also be made for some parameters using electronic instruments.

Fixed Location In Situ Sensors

In situ sensors (Continuous Monitors) can be affixed to buoys, piers, or other fixed objects. These systems can provide measurements at short intervals over an extended period of time between service calls by support personnel. Thus, buoy systems provide data with relatively high temporal resolution. Such data can be particularly useful for parameters that exhibit a high degree of temporal variability. Unfortunately, the cost of buoy systems limits their number and thereby restricts spatial coverage and resolution. Such systems can be used to monitor dissolved oxygen, fluorescence, turbidity, water temperature, salinity, and pH. Measurements are made every 15 minutes, typically at 1-meter depth. These data can be telemetered real-time to the collecting agency or stored by the instrument for periodic download by a technician. The data yielded by these systems can be used to infer temporal changes at other similar locations where such data are not available.

Continuous Underway Monitoring

Continuous underway monitoring (Water Quality Mapping) refers to collection of data at very short time intervals as a boat moves along a transect or a series of transects. The sensors can be towed *in situ*, or water can be pumped through an on-board sensor as the boat moves along the transect. Measurements can be made over a range of depths by raising and lowering the sensor or water intake as it moves along the transect.

The principle advantage of continuous underway monitoring is the very high spatial resolution of the data that it yields. Data along transects are virtually continuous, and transects can be spaced as closely as is needed to allow later interpolation between transects. While consecutive samples are close together in time, it takes several hours to sample an entire assessment unit. Parameters such as dissolved oxygen can exhibit significant diel changes during the time required to sample a given assessment unit. High frequency data at a fixed location can be used to infer dissolved oxygen concentrations at other times and thereby be used to adjust observations collected over several hours to a single point in time.

The Water Quality Mapping system collects data every 3-5 seconds while traveling at speeds up to 2.5 knots. The Maryland Department of Natural Resources and the University of Maryland Center for Environmental Science Chesapeake Biological Laboratory have evaluated this system in several Chesapeake Bay tributaries. Available parameters include dissolved oxygen, fluorescence, turbidity, water temperature, and salinity. The Water Quality Mapping system requires two people: one to operate the boat and one to operate the system. Each team can monitor approximately 100 km of linear transects in a day.

Summary of Design Alternatives Considered

Table 5 summarizes alternatives considered by the design team for the various components of the monitoring network. Justification for inclusion or exclusion of alternatives is provided in the next section.

Table 5. Initial proposed tidal monitoring components listed by objectives / designated use.

Objective: Characterization, Status - Criteria Attainment			
	Dissolved Oxygen	Chlorophyll a	Clarity
Migratory Spawning And Nursery	Fixed-Station Network – Spatially enhance where needed Buoy System – Strategically located	Fixed-Station Network - To cover open-water areas Probability-Based Network - To cover shallow-water areas DataFlow – Episodic / Strategic Basis Remote Sensing - Episodic to map the spatial extent of blooms Continuous underway monitoring on cruise ships	
Shallow Water	Probability-Based Network – Base-line spatial extent DataFlow – Episodic / Strategic Basis Buoy System – Strategically located		Probability-Based Network – Base-line spatial extent DataFlow – Episodic / Strategic Basis Buoy System – Strategically located
Open Water	Fixed-Station Network – Spatially enhance where needed Buoy System - Strategically located and moved intermittently Continuous underway monitoring on cruise ships		
Deep Water	Current Fixed-Station Network Buoy System – Strategically located and moved intermittently		
Deep Channel	Current Fixed-Station Network Buoy System – Strategically located and moved intermittently		

Objective: Characterization, Status – Water-Quality Goals			
	Total Nitrogen	Total Phosphorus	Sediment
Migratory Spawning And Nursery	Fixed-Station Network – Spatially enhance where needed		
Shallow Water	Probability-Based Network – Base-line spatial extent		
Open Water	Fixed-Station Network – Spatially enhance where needed		
Deep Water	Current Fixed-Station Network		
Deep Channel	Current Fixed-Station Network		

Objective: Characterization, Status – Biotic Indicators

	Phytoplankton	Zooplankton	Benthos	SAV	Chlorophyll a
Migratory Spawning And Nursery		Fixed-Station Network – Spatially enhance where needed			Fixed-Station Network - To cover open-water Probability-Based Network - To cover shallow-water DataFlow – Episodic / Strategic Basis Remote Sensing - Episodic to map the spatial extent of blooms Continuous underway monitoring on cruise ships
Shallow Water	Probability-Based Network – Base-line spatial extent		Probability-Based Network – Base-line spatial extent	Probability-Based Network – Base-line spatial extent	
Open Water	Fixed-Station Network – Spatially enhance where needed				
Deep Water					
Deep Channel					

Objective: Trends			
	Criteria Parameters	Water-Quality Reduction Goal Parameters	Biotic Index Parameters
Migratory Spawning And Nursery	Fixed-Station Network – Spatially enhance where needed		
Shallow Water	Probability-Based Network		
Open Water	Fixed-Station Network – Spatially enhance where needed		
Deep Water	Current Fixed-Station Network		
Deep Channel	Current Fixed-Station Network		

Objective: Modeling			
	Criteria Parameters	Water-Quality Reduction Goal Parameters	Biotic Index Parameters
Migratory Spawning And Nursery	[redacted]		
Shallow Water			
Open Water	Fixed-Station Network – Spatially enhance where needed		
Deep Water	Current Fixed-Station Network		
Deep Channel	Current Fixed-Station Network		

Recommended Approach

The monitoring network design developed by the team is summarized in Table 6. It integrates multiple methods of data collection and to a large degree builds upon the existing network developed and implemented in 1984 and evaluated by internal and external monitoring experts on numerous occasions over the last 2 decades. For the most part, the initial long-term comprehensive Chesapeake Bay Monitoring Program has remained in tact. The recommended enhancements to the design are described below, along with justification for key design choices and cost estimates.

Description and Justification

The recommended monitoring network design shares many important characteristics with the existing monitoring network, including the segmentation scheme that has been in place since 1993 (Figure 3). The most significant changes to the monitoring network derive from the intersection of the Bay segmentation with the new Chesapeake Bay designated uses (Figure 2) and the resulting large number of shallow water assessment units. The Bay interpolator and future upgrades will remain an important tool for characterizing water quality, and the interpolator will interpolate across assessment unit boundaries. Defensible assessments are needed for each assessment unit, however, and this requires suitable distribution of observations among assessment units and within each assessment unit. The existing monitoring network is particularly deficient with respect to the shallow water assessment units.

Attainment/non-attainment of water quality criteria must be reported on a three-year cycle. A minimum of three years of data are needed to reasonably characterize the status of a given assessment unit. The 3-year assessment period is necessary to account for inter annual variability as driven by high and low flow conditions. The existing comprehensive long-term Chesapeake Bay Monitoring Program meets most of the data needs for assessing the water quality criteria in open, deep and deep channel designated uses as well as for evaluating water quality changes or trends over time. The design team also recommends the implementation of shallow water monitoring comprised of both continuous and water quality mapping to be conducted over a 3-year assessment period as well. Individually, these shallow water segments require a substantial increase in sampling effort, and collectively they are too numerous to sample every year for trends. Consequently, the State of Maryland and the Commonwealth of Virginia will establish schedules for assessment of these units over 3-year periods that reflect regulatory priorities and funding constraints. Details on comprehensive long-term Chesapeake Bay Monitoring Program and Shallow Water Monitoring Program equipment, sampling methods, parameters, data management and data analysis can be found in the Maryland DNR and Virginia DEQ Shallow Water Monitoring Quality Assurance Project Plans. (references)

Data collection is distributed through the year consistent with the requirements of the new Chesapeake Bay water quality criteria. Scheduling of data collection within these broad requirements is based on logistical considerations such as vessel requirements and travel distances. Temporal randomization of data collection within seasonal strata was considered impractical because of those logistical considerations.

Additional description and justification of the monitoring network design is organized by collection method. For each collection method included in the recommended network design, the other design factors are discussed and the choices are justified.

Table 6. Recommended tidal monitoring components listed by objectives / designated use.

Objective: Characterization, Status - Criteria Attainment			
	Dissolved Oxygen	Chlorophyll a	Clarity
Migratory Spawning And Nursery	Fixed-Station Network – Spatially enhance where needed Buoy System – Strategically located	Fixed-Station Network - To cover open-water areas DataFlow – Routine basis during growth season Remote Sensing - Routine basis to map the spatial extent of blooms Continuous underway monitoring on cruise ships	
Shallow Water	DataFlow – Routine basis during growth season Buoy System – Strategically located		DataFlow – Routine basis during growth season Buoy System – Strategically located
Open Water	Fixed-Station Network – Spatially enhance where needed Buoy System - Strategically located and moved intermittently Continuous underway monitoring on cruise ships		
Deep Water	Current Fixed-Station Network Buoy System – Strategically located and moved intermittently		
Deep Channel	Current Fixed-Station Network Buoy System – Strategically located and moved intermittently		

Objective: Characterization, Status – Water-Quality Goals			
	Total Nitrogen	Total Phosphorus	Sediment
Migratory Spawning And Nursery	Fixed-Station Network – Spatially enhance where needed		
Shallow Water	DataFlow – Routine basis during growth season Buoy System – Strategically located		
Open Water	Fixed-Station Network – Spatially enhance where needed		
Deep Water	Current Fixed-Station Network		
Deep Channel	Current Fixed-Station Network		

Objective: Characterization, Status – Biotic Indicators

	Phytoplankton	Zooplankton	Benthos	SAV	Chlorophyll a
Migratory Spawning And Nursery		Fixed-Station Network – Spatially enhance where needed			Fixed-Station Network - To cover open-water DataFlow – Routine basis during growth season Buoy System – Strategically located Remote Sensing - Routine basis to map the spatial extent of blooms Continuous underway monitoring on cruise ships
Shallow Water	Probability-Based Network – Base-line spatial extent		Probability-Based Network – Base-line spatial extent	Aerial Survey	
Open Water	Fixed-Station Network – Spatially enhance where needed				
Deep Water					
Deep Channel					

Objective: Trends			
	Criteria Parameters	Water-Quality Reduction Goal Parameters	Biotic Index Parameters
Migratory Spawning And Nursery	Fixed-Station Network – Spatially enhance where needed		
Shallow Water	DataFlow – Routine basis during growth season Buoy System – Strategically located		
Open Water	Fixed-Station Network – Spatially enhance where needed		
Deep Water	Current Fixed-Station Network		
Deep Channel	Current Fixed-Station Network		

Objective: Modeling			
	Criteria Parameters	Water-Quality Reduction Goal Parameters	Biotic Index Parameters
Migratory Spawning And Nursery	[redacted]		
Shallow Water			
Open Water	Fixed-Station Network – Spatially enhance where needed		
Deep Water	Current Fixed-Station Network		
Deep Channel	Current Fixed-Station Network		

Remote Sensing

Remote sensing was considered for chlorophyll and water clarity assessment. Remote sensing was of particular interest for chlorophyll assessment because of the patchiness of algal blooms and the fine-scale spatial resolution and broad-scale spatial coverage of remote sensing data. Both satellite- and aircraft-based methods were considered. Remote sensing was included in the recommended design because of the need for greater spatial resolution in chlorophyll criteria assessment. However, its implementation was delayed, because of concerns regarding calibration and interference by suspended sediments, flight restrictions, and a variety of other uncertainties. It was ultimately decided that a pilot study is necessary to resolve all the uncertainties regarding the application of remote sensing for criteria assessment in the Chesapeake Bay. Until that pilot study is completed, the remote sensing option would not be implemented. Alternative collection methods (e.g., continuous underway monitoring) can simultaneously collect data for chlorophyll and other parameters in shallow water areas. However, no alternative methods are available for the open waters of the Bay and remote sensing is considered to be an essential monitoring component for chlorophyll criteria assessment in such areas.

Grab Samples

Grab samples form the backbone of the existing monitoring network, and they remain so for the network recommended by the design team. The grab samples are collected at a network of fixed stations located to support interpolation of parameter values throughout the open water, deep water, and deep channel areas. Additional observations will be needed to assess conditions in shallow water areas. With a vessel and crew on site, all measurements or collections of interest can be made, be they physical or chemical measurements, or biological samples. Furthermore, the observations are coincident in space and time, which facilitates data analysis and interpretation. The data collected via grab samples under the recommended network design will be compatible with data collected under the existing monitoring network. This will permit long-term trend analysis using both old and new data.

Continuous Underway Monitoring – Water Quality Mapping

The new Chesapeake Bay designated uses and water quality criteria are the driving force behind the redesign of the monitoring program. All 3 parameters – chlorophyll, water clarity and dissolved oxygen – require enhancement of the existing network design. These parameters exhibit a high degree of spatial variability, especially in the shallow water assessment units. Dissolved oxygen also exhibits substantial diel variability. Continuous underway monitoring can provide data with the spatial resolution needed to assess chlorophyll, water clarity and dissolved oxygen in these areas. In addition to dissolved oxygen and chlorophyll (fluorescence), continuous underway monitoring can provide temperature, salinity, and turbidity data. Turbidity data is used to assess water clarity.

As noted above, 4-8 hours are needed to survey a given segment with continuous underway monitoring depending on the size of the segment. Given travel and setup time and cruise time, generally only one segment can be sampled in a day. Larger segments, such as the Patuxent and Potomac River will require multiple days to assess. Consequently, equipment costs and logistical constraints limit the number of units that can be assessed in any single year. With current resources obtained by Maryland and Virginia, it is estimated that the assessments of all Chesapeake Bay shallow water habitats will be completed by 2018 at the earliest. The schedule of segments to be assessed will be developed by the State of Maryland and the Commonwealth of Virginia to reflect their respective priorities and funding constraints.

Given that a significant amount of diel variation can occur during the time required to survey a segment, the data produced by continuous underway monitoring must be adjusted using high frequency data such as that provided by fixed location continuous monitors (discussed below).

Fixed Location Continuous Monitors

A network of continuous monitors will provide high frequency data for several parameters at selected fixed locations. Sensors will be placed on buoys in the Chesapeake Bay mainstem and in the central portion of major tributaries if resources can be identified. It should be noted that these fixed continuous monitors are the only way to assess the higher frequency dissolved oxygen criteria components. Continuous monitors will be placed on piers and other fixed objects in shallow water areas and moved to coincide with the assessment units that are being surveyed with continuous underway-monitoring devices.

Continuous monitors affixed to buoys can telemeter their data to receiving stations on a regular basis if desired and resources permit, and data from pier-mounted devices will be downloaded on a regular schedule dictated by the memory capacity of the unit. This information will provide vital information for placing the data collected by other means in the context of temporal variation. It will also provide the basis for adjusting dissolved oxygen data collected over many hours throughout an assessment unit to a point in time. That time may be dictated by the characteristics of the high frequency data and by the regulatory requirements of the dissolved oxygen criteria.

To date funds are available to locate continuous monitors in the shallow-water designated use areas only in association with water-quality mapping. However, because of the expense and the logistical difficulty of locating and maintaining continuous monitors in the open areas of the Bay, the implementation of this recommended component also has been delayed. Ultimately the expenditure of some funds for open water continuous monitors will be necessary for the assessment of the higher frequency dissolved oxygen criteria components. However funds have not been allocated to date and this will remain a gap in the CBP's criteria assessment capability.

Provisionally Adopted Network Design

A network design has been provisionally adopted for planning purposes. The broad features of that design are listed in Table 7.

Table 7. Tidal monitoring components that were implemented as of 2004, listed by objectives / designated use.

Objective: Characterization, Status - Criteria Attainment			
	Dissolved Oxygen	Chlorophyll a	Clarity
Migratory Spawning And Nursery	Existing fixed-Station Network	Existing fixed-Station Network DataFlow – Routine basis during growth season - Shallow water and small tributaries only Buoy System – Strategically located - Shallow water and small tributaries only	
Shallow Water	DataFlow – Routine basis during growth season Buoy System – Strategically located		DataFlow – Routine basis during growth season Buoy System – Strategically located
Open Water	Existing fixed-Station Network		
Deep Water	Existing fixed-Station Network		
Deep Channel	Existing fixed-Station Network		

Objective: Characterization, Status – Water-Quality Goals			
	Total Nitrogen	Total Phosphorus	Sediment
Migratory Spawning And Nursery	Existing Fixed-Station Network		
Shallow Water	DataFlow – Routine basis during growth season Buoy System – Strategically located		
Open Water	Existing Fixed-Station Network		
Deep Water	Existing Fixed-Station Network		
Deep Channel	Existing Fixed-Station Network		

Objective: Characterization, Status – Biotic Indicators					
	Phytoplankton	Zooplankton	Benthos	SAV	Chlorophyll a
Migratory Spawning And Nursery		Existing Fixed-Station Network			Existing Fixed-Station Network DataFlow – Routine basis during growth season - Shallow water and small tributaries only Buoy System – Strategically located - Shallow water and small tributaries only
Shallow Water			Probability-Based Network – Base-line spatial extent	Aerial Survey	
Open Water	Existing Fixed-Station Network				
Deep Water					
Deep Channel					

Objective: Trends			
	Criteria Parameters	Water-Quality Reduction Goal Parameters	Biotic Index Parameters
Migratory Spawning And Nursery	Existing Fixed-Station Network		
Shallow Water	DataFlow – Routine basis during growth season Buoy System – Strategically located		
Open Water	Existing Fixed-Station Network		
Deep Water	Existing Fixed-Station Network		
Deep Channel	Existing Fixed-Station Network		

Objective: Modeling			
	Criteria Parameters	Water-Quality Reduction Goal Parameters	Biotic Index Parameters
Migratory Spawning And Nursery	[redacted]		
Shallow Water	[redacted]		
Open Water		Existing Fixed-Station Network	
Deep Water		Existing Fixed-Station Network	
Deep Channel		Existing Fixed-Station Network	

Outstanding Issues and Future Work

The design process has unfolded in an environment of changing, incompletely defined regulatory requirements and decision criteria and limited monitoring budgets. Furthermore, the monitoring design makes use of technologies and methods of data analysis that are not part of the existing monitoring and assessment program. The Chesapeake Bay interpolator is being updated, and new methods of defining water quality criteria are under development. Details of data analysis methods, decision rules, and interpolation algorithms remain to be worked out. Consequently, the information does not yet exist to rigorously evaluate some aspects of the recommended monitoring network design. Additional work is required to define data quality objectives and to support a more detailed monitoring network design.

References Cited

USEPA. 2003. *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay and Its Tidal Tributaries*. U.S. Environmental Protection Agency, Washington, DC.EPA 903-R-03-002.

APPENDIX A

Tidal Water Quality Design Task Group

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APPENDIX B

Summary of Chesapeake Bay dissolved oxygen criteria.

Designated Use/Habitat	Criteria	Applicable Time Period
Migratory Spawning and Nursery	7-day mean ≥ 6 mg liter $^{-1}$ Instantaneous minimum ≥ 5 mg liter $^{-1}$	February 1 to May 31
Shallow Water/Open Water	30-day mean ≥ 5 mg liter $^{-1}$	January 1 to December 31
Deep Water	30-day mean ≥ 3 mg liter $^{-1}$	June 1 to September 30
Deep Channel	Instantaneous minimum ≥ 1 mg liter $^{-1}$	June 1 to September 30

Summary of Chesapeake Bay water clarity criteria.

Salinity Regime	Water Clarity Criteria as Percent Ambient Light		Temporal Application
	Light through Water	Light at the Leaf	
Tidal Fresh	13%	9%	April-October
Oligohaline	13%	9%	April-October
Mesohaline	22%	15%	April-October
Polyhaline	22%	15%	March-May, September-November

Summary of Chesapeake Bay chlorophyll *a* criteria (µg liter $^{-1}$)

Salinity Regime	Chesapeake Bay Chlorophyll *a* Criteria	
	Spring (March-May)	Summer (July-September)
Tidal Fresh	20	25
Oligohaline	25	25
Mesohaline	30	20
Polyhaline	15	15